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Zirconia Ceramic Fixed Partial Dentures after Cyclic Fatigue Tests and Clinical Evaluation: A Systematic Review

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Abstract

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Key Words

Zirconia, fatigue, fixed prosthetic denture, thermocycling, all-ceramic, FPD, *in vitro*, clinical;

Introduction

The new dental ceramic materials and contemporary computer-aided techniques have been successfully introduced into routine dental practice during the last two decades. In vitro evaluation of new materials and techniques is essential before routine clinical use [1]. The results of previous in vitro studies enable more predictable prosthetic restorations with a better long-term clinical success. Clinically based evidence is another key factor for predicting survival and longevity of different dental materials for prosthetic rehabilitation of missing or destroyed teeth.

Fixed partial dentures (FPDs) are the type of dental restorations, permanently attached to adjacent teeth, used to replace missing teeth. They can be produced by conventional all-metal or porcelain-fused-to-metal technique or by contemporary all-ceramic materials [2]. The development of framework (substructure) ceramics for fixed

prosthodontics represents the transition toward polycristalline ceramic materials [3]. The use of all-ceramic dental restorations has risen significantly due to biocompatibility and favorable esthetics [4, 5]. Additionally, possible adverse reactions of metal alloys on tissues have accelerated the development of a metal – free ceramic dental restorations [6].

Zirconia ceramics was introduced into clinical practice in 1990, but the development of computer–aided design and computer–aided manufacturing (CAD/CAM) technology has driven the progress, which opened the pathway to the production of individually designed FPDs [7]. Yttria partially stabilized tetragonal zirconia (Y-TZP) is unique among other dental ceramics because of its superb tissue compatibility, superior strength, fracture toughness and damage tolerance [8]. Due to the opaque appearance of the first generation Y-TZP it is mainly used as the framework material, that is veneered with porcelain to achieve the final form and esthetics.[9]. Bilayered FPDs have unfortunately shown high incidence of veneer fractures [10].

Clinical use of all-ceramic FPDs in posterior area is often connected with chipping or fracturing of the veneering porcelain [9]. Less porcelain delamination from ceramic framework can be attained by anatomical shaping of ceramic frameworks and with the use of veneering porcelains with thermal expansion coefficient adapted to framework

ceramics [9]. Frequent chipping of veneering porcelain and the development of translucent zirconia ceramics have dictated the introduction of monolithic zirconia ceramic restorations without veneering porcelain [9]. The advantages of monolithic zirconia ceramic restorations in comparison to glass – ceramic and porcelain veneered zirconia ceramic restorations are greater strength, a more conservative preparation of teeth, great precision and complete computer-aided manufacturing.

To be able to vouch for a new type of dental material extensive clinical studies ought to be carried out [11]. Still, in vitro studies involving fatigue testing, which simulate the clinical situation as close as possible, have a high translational meaning [11, 12]. One can identify two different strands of in vitro studies: (1) physical property measurements and (2) simulations of clinical behaviour [13]. The second group of in vitro studies attempts to create the same conditions that are believed to be encountered in the oral cavity (fatigue testing), therefore cyclic or monotonic loading, thermal variations and wear of material were applied [13].

Therefore a systematic review is needed to compare the results of the in vitro studies and survival rate of the zirconia FPDs after clinical use. The objective of this systematic review therefore was to elaborate the in vitro studies and

clinical trials conducted on zirconia FPDs and to serve as a guideline for more comparable future experimental work on zirconia ceramics.

Materials and methods

Search Strategy

Two electronic searches at PubMed (MEDLINE) database were conducted for English articles about clinical and in vitro studies on zirconia restorations. In the first search the following MeSH terms, search terms and combinations of those were used: "in vitro", "fatigue", "fixed dental prosthesis", "zirconia", "cyclic", "FDP", "FPD", "bridges", "Y-TZP", "loading". This search provided 556 articles, which were to be screened further for possible inclusion in the review. For the second search the following MeSH terms, search terms and combinations of those were used: "clinical", "survival", "fixed dental prosthesis", "zirconia", "all-ceramic", "FDP", "FPD", "bridges", "Y-TZP". This search provided 288 articles, which were to be screened further for possible inclusion in the review. Additionally, a manual search for the articles covering the period from 01/01/1996 up to and including 01/09/2017 was conducted.

In addition, hand searches were performed on references of the selected articles to discover whether in the search process any relevant article was unaccounted for.

Inclusion/Exclusion Criteria

Journal articles in English concerning in-vitro and clinical studies of only zirconia fixed partial dentures were included in the review. There are few studies conducted on zirconia ceramic fixed dental prosthesis, all of them were included, even if there was some missing information. Articles were not included if they included implants, inlays, overlays, posts, inlay-retained bridges, all-ceramic crowns, any other restorations from all-ceramic material except zirconia. Extension units and cantilever FPDs were also not included. This review concentrated exclusively on bilayered zirconia FPD and monolithic FPD restorations.

Study Selection

The first search process yielded 556 journal articles, which were reviewed by an independent reviewer for possible inclusion in this systematic review. After title screening 185 abstracts were selected and evaluated. After evaluation 90 full-text articles were found and read. Finally 11 articles were included in this review. The second search process yielded 288 journal articles, which were reviewed by an independent reviewer for possible inclusion in this systematic review. After title screening 96 abstracts were selected and evaluated. After evaluation 48 full-text articles were found and read. Finally 28 articles were included in this review.

Data Extraction

All the information from the studies was recorded and tabulated in Excel sheets. The information that could not be calculated or extracted was marked as "not available (n.a.)".

Table 1: Details of in vitro studies on zirconia fixed prosthetic dentures

					Fatigue conditions				Loading until failure	
Authors, year	Framework ceramic	Veneering ceramic	Specimens and location	Fracture strength (N) *before fatigue*	Number of cycles	Force (N)	Temperature (°C)	Indenter	Fracture strength (N) *after fatigue*	Indenter
Larsson et al., 2007 [14]	Procera Zirconia	NobelRondo™ Zirconia	40 4-unit FPD Posterior	n.a.	1 x 10^4	30 - 300	5 - 55	2.5 mm stainless steel ball	300 - 897	2.5 mm stainless steel ball
Att et al., 2007 [15]	DCS/Procera/ Cerec inLab	Porcelain (VM9, Vita)	48 3-unit FPD Posterior	DCS: 2071 Procera: 1730 Cerec: 1771	1,2 x 10^6	49 N	5 - 55	6 mm ceramic ball	DCS: 1823 Procera: 1396 Cerec: 1630	Steel wedge 1 cm x 0.8 cm
Kohorst et al., 2008 [4]	Cercon base, DeguDent, Hanau, Germany	Veneering n.a.	60 4-unit Posterior	1525 ± 76.5	1 x 10^6/2 x 10^6	100/200	5 - 55	n.a.	903.7 ± 40.8 923.5± 40.3 952.4 ± 51.4	6 mm tungsten carbide ball
Beuer et al., 2008 [16]	Semi-sintered zirconia (InCeram YZ)	Porcelain (VM7 Vita)	20 3-unit FPD Posterior	981 ± 266	1,2 x 10^6	50	5 - 55	6 mm tungsten carbide ball	1042 ± 195	10 mm tungsten carbide ball
Kohorst et al., 2010 [17]	InCeram YZ, Vita	Porcelain (VM9,Vita)	40 4-unit FPD Posterior	1991.4	1 x 10^6	100	5 - 55	n.a.	1600	6 mm tungsten carbide ball

Rosentritt et al., 2011 [18]	Zirkograph, Zirkonzahn	ICE, Zirkonzahn	40 3-unit FPD Posterior	n.a.	1,2 x 10^6	50	5 - 55	n.a.	1011/2126	12 mm steel ball
Preis et al., 2012 [19]	Cercon brain, DeguDent, Hanau, Germany	Cercon ceram kiss, DeguDent	56 3-unit FPD Posterir	n.a.	1,2 x 10^6	50	5 - 55	12 mm steel ball	1063.3/1272.0 1037.0/1441.8	12 mm steel ball
Eroğlu and Gurbulak, 2013 [2]	Copran zircon blanks, White Peaks Dental Systems GmbH & Co. Essen, Germany	Ceramic	20 3-unit FPD Posterior	2434.9 ± 154.34	1 x 10^5	50	5 - 55	n.a.	2333.1 ± 183.02	3 mm stainless steel ball
Mahmood et al., 2013 [20]	Procera Zirconia	Ivoclar P 500, Ivoclar Vivadent AG	16 3-unit 16 4-unit FPD Anterior	n.a.	1 x 10^4	30 - 300	5 - 55	2.5 mm stainless steel intender	405 - 910	Stainless steel intender
Campos et al., 2016 [21]	Vita In-Ceram 2000 YZ cubes, Vita Zahnfabrik	Vita VM9, Vita Zahnfabrik	40 3-unit FPD Posterior	n.a.	1 200 000	200 N	n.a.	n.a.	1958 ± 299	n.a.
Oblak et al. [9]	InCoris TZI, Sirona, Germany	/	30 monolithic 4-unit FPD Posterior	547.3 ± 66.3	1 x 10^6	0 - 300	37	6 mm stainless steel ball	408.8 ± 58.9	6 mm stainless steel ball

Table 2: Details of clinical studies on zirconia fixed prosthetic dentures

Author, year	Study type	Zirconia system	Follow-up time	Number of restorations	Framework fracture (%)	Veneering porcelain fracture (%)	Survival rate (%)
Vult von Steyern et al., 2005 [22]	Prospective	DC-Zirkon (DSC Dental)	2 years	20 3-5 unit	0	15	100
Raigrodski et al., 2006 [23]	Prospective	Lava (3M ESPE)	2,5 years	20 3-unit	0	25	100
Sailer et al., 2007 [24]	Prospective	Cercon Base (Dentsply)	5 years	33 3-5 unit	2.2	15.2	73.9
Tinschert et al., 2008 [25]	Prospective	DC-Zirkon	3 years	65 3-5 unit	0	6	100
Molin et al., 2008 [26]	Prospective	Denzir (Cad. Esthetics)	5 years	19 3-unit	0	30	100
Crisp et al., 2008 [27]	Observational study	Lava	5 years	38 3-4 unit	0	3	100
Edelhoff et al., 2008 [28]	Prospective	DigiZin (AmannGirrbach)	3 years	22 3-6 unit	0	9	100
Schmitter et al., 2009 [29]	Prospective	Cercon base	2 years	30 4-7 unit	3	3	96.7

Wolfart et al., 2009 [30]	Prospective	Cercon base	4 years	58 3-4 unit	0	5	96
Sailer et al., 2009 [31]	Controlled Clinical Trial	Cercon base	3 years	36 3-5 unit	0	25	100
Schmitt et al., 2009 [32]	Prospective	Lava	3 years	27 3-4 unit	0	11	100
Beuer et al., 2009 [33]	Prospective	Cercon base	3 years	21 3 unit	5	0	90.5
Roediger et al., 2010 [34]	Prospective	Cercon base	4 years	99 3-4 unit	1	13	94
Sax et al.,2011 [35]	Prospective	Zirconia DCM	10 years	26 3-5 unit	11.5	32	67
Lops et al., 2012 [36]	Prospective	n. a.	6.5 years	24	4	4	88.9
Salido et al., 2012 [37]	Prospective	Lava	4 years	17 4-unit	17.6	29.4	76.5
Pelaez et al., 2012 [38]	Prospective	Lava	3 years	20 3 unit	0	10	95
Sorrentino et al., 2012 [39]	Prospective	Procera, Procera All Zircon	5 years	48 3 unit	0	6.25	100
Schmitt et al., 2012	Prospective	Lava	5 years	30 3-4 unit	3	20	92

[40]							
Burke et al., 2013 [41]	Observational Study	Lava	5 years	33 3-4 unit	0	39	97
Rinke et al., 2013 [42]	Prospective	Cercon base	7 years	99 3-4 unit	4	23	83.4
Håff et al., 2015 [43]	Retrospective	HIP Y-TZP Denzir	13 years	33 3-6 unit	0	9.7	94
Monaco et al., 2015 [44]	Retrospective	n.a.	5 years	137	2.2	7.3	94.7
Naenni et al., 2015 [45]	Controlled Clinical Trial	IPS e.max + IPS e.max ZirPress	3 years	36 3 unit	0	30	100
Sola-Ruiz et al., 2015 [46]	Prospective	Lava	7 years	27 3-6 unit	0	14.8	88.8
Ioannidis et al., 2016 [47]	Prospective	ZYrcomat + Vitadur Alpha	10 years	59 3-unit	0	28	85
Pihlaja et al., 2016 [48]	Retrospective	Zirkonzahn, Nobel Procera, Prettau zirconia	4.9 years	120 3-12 units	0	14.7	100
Norström Saarva et al., 2017 [49]	Retrospective	HIP Denzir	3 years	184 2-8 units	1.1	7.6	95.2

Results

The selection process derived the final sample of 11 journal articles with in vitro tests [2, 4, 9, 14, 15, 16, 17, 18, 19, 20, 21] and 28 journal articles with clinical studies [22 ¬ 49]. All the articles are dealing with the FPDs made from zirconia framework and veneered with porcelain and one article is on monolithic zirconia.

In vitro studies

Considering that the in vitro studies on FPDs are usually more expensive than on crowns, there are not a lot of them to choose from. Table 1 displays eleven of in vitro studies included. The number of fatigue cycles varied between a minimum of 10 000 to a maximum of 1 200 000 cycles. The applied force during cyclic loading varied between 30 and 300 N for 3- or 4-unit FPDs. The temperature of fatigue chambers varied between 5 and 55°C. In half of the studies listed in the Table 1 the fracture strength before fatigue testing was not listed (n.a. = not available). In the other half of the listed studies decreased values of the fracture strength after fatigue testing could be observed. After static loading only the measured values of fracture strength were 1525 ± 76.5 to 2434.9 ± 154.34 N. After cyclic

loading the measured values decreased, the measured values went from 903.7 ± 40.8 to 2333.1 ± 183.02 N. The only exception is the study from Beuer et al. [16], where there is no influence of the ageing process to be observed, as the fracture strength value after fatigue testing is higher than before. In the study from Oblak et al. [9] 30 glazed monolithic zirconia FPDs were fatigue tested. The measured value of fracture strength decreased from 547.3 ± 66.3 N to 408.8 ± 58.9 N.

Clinical trials

Table 2 shows the list of 28 clinical studies, twenty of them being prospective, four of them being retrospective, two are observational studies and the last two are controlled clinical trials. In these studies, 1381 zirconia-veneered FPDs were tested and 60 ceramics-fused-to-metal FPDs for comparison. The shortest observational period was 2.6 years and the longest 9.6 years. The average rate of survival of the zirconia- veneered FPDs was 91.73 %. The most frequent technical complications were veneer fracture (17.1 %), framework fracture (2.8 %) and decementation (2.3 %). The most frequent biological complications were secondary caries (2 %) and endodontic treatment (1.9 %). Periodontal treatment was necessary in one case only.

Discussion

In vitro Evaluation

In vitro investigations are compared to clinical studies easier to reproduce and less vulnerable to unpredictable failures during clinical use [16]. Due to a great variation of in vitro parameters of fatigue testing of dental restorations, standardization of testing procedures is needed for suitable (real) ranking mechanical durability of FPDs [1, 9, 13].

In the previous studies there is a great variation of in vitro testing simulation parameters: thermocycling, different jaw movements, type of abutments, artificial teeth support, antagonistic teeth, number of fatigue cycles, indenter geometry, which may cause different outcomes [12, 50].

Posterior FPDs require a loading capability of more than 500 N for molars and less than 500 N for premolars [1, 16, 19, 50]. The values of fracture strength after fatigue show that all the FPDs tested could be designed in posterior

region. In many studies there is no data about fracture strength before fatigue cycling, therefore we cannot deduce clinically relevant conclusions [1].

Aqueous oral environment promotes the subcritical crack growth and causes the transformation into the monoclinic structure of Y-TZP via stress-corrosion-type mechanism [4, 8, 51]. Temperature changes, moisture and mechanical loading during chewing are ideal conditions for low temperature degradation (LTD) to arise and influence the long-term prognosis of FPDs [16, 51]. Although water storage before thermocycling was used, almost all the zirconia FPDs in-vitro studies were veneered with porcelain, which protects core zirconia ceramic against hydrothermal degradation. Also in the study from Oblak et al. [9], where monolithic glazed FPDs were tested, the drop in fracture load was similar as in bi-layered specimens and was ascribed to stress corrosion. In the latter study they concluded that accelerated ageing did not influence the survival rate of FPDs, but there was an estimated difference in fracture load values between the un-aged and aged FPDs. Nevertheless, no systematic ageing study with dental ceramics under true clinical conditions has been conducted so far [8]. Temperature of the chambers of all in-vitro studies was between 5 and 55 °C.

The lateral jaw movement seems to be a topic for further research, as side shift chewing forces may initiate cracks and chipping of the porcelain [19]. In different in vitro studies different abutment materials were used; nickel–chromium alloy [52], stainless steel [6], natural human teeth [53], and polyurethane – PUR [4, 9]. Material used for abutments in in vitro studies has a strong impact on fracture resistance of FPDs [4, 19]. PUR material has elastic modulus lower than dentin and alveolar bone, but has so far offered the closest resemblance to natural conditions [9]. Fracture strength may also be dependent on a supporting setup, as rigid teeth have shown the result which was three times higher than with the artificial periodontium, made of polyether or silicon material [11]. Periodontal resilience is necessary during fatigue testing of the specimens, if we want to get reliable results of fracture resistance.

The number of fatigue cycles in the in vitro test was of 10 000 to 2 000 000 cycles, as is shown in Table 1. It was estimated that $2 \times 10_6$ cycles represent approximately 4 years of normal occlusal and masticatory activity [1]. Therefore, for all future in vitro tests the same number of cycles for in vitro testing, at least $2 \times 10_6$ cycles, should be recommended, so that the results would be more comparable and relevant.

The forces used in the fatigue tests of in vitro studies were between 30 and 300 N. If we assume that the mean masticatory forces are from 12 N to 70 N [50], the forces used in tests are suitable for simulation of a clinical situation.

It is however difficult to determine the mean masticatory forces. Larsson et al. [14] even report that the maximum occlusal bite forces vary from few hundred N in the anterior area to more than a thousand N in molar areas. Higher values are possible when the clenching or bruxism disorder is present, lower values have been reported for women, elderly persons, denture wearers and patients with dysfunction of the masticatory system [14].

Dimensions of indenters used in in vitro tests were from 2.5 to 12 mm diameter made from stainless steel or carbide in ball or wedge form loaded FPDs from occlusal surface. It is important to consider the kind of indenters used in tests as the diameter and sharpness of the indenter influence the formation of cone crack or Hertzian crack [1]. Antagonists used for simulation are also to be carefully considered, if we want to get clinically relevant results. Although spherical indenters vouch for a standardized antagonist in the form of natural teeth, antagonists would be the only relevant option for acquiring the relevant loading and wear behavior [19].

Mechanical properties of FPDs could be strongly dependent on variable factors – connector dimension and shape, framework design, distance between abutments [21]. Connector design seems to be crucial for the fracture resistance and durability of FPDs [54]. In general, the cross-sectional area of the connector should be as large as possible, as they are crucial for strength and long durability of FPDs [2, 20, 55], but on the other side they influence the aesthetic

and hygienic aspect. For in vitro studies that means that extending the area of the connector increases the fracture load [54]. Connector area should be at least 7.0 mm^2 or more, especially for long-span FPDs [54]. Anatomically reduced framework design ensures the optimal support and an even thickness of the veneering porcelain [19]. Cusp design is also important as rounded cusps and flat angles are beneficial for force distribution during chewing and therefore lower chipping rate [18, 19].

Clinical Evaluation

Clinical trials are expensive and usually delayed for about eight to ten years after a certain product has been proved and recommended for safe clinical use [56]. We have no comparative clinical follow-up studies for the different types of Y-TZP and their respective properties [49]. In the 28 clinical studies gathered, where veneered zirconia–FPDs were observed, a different type of Y-TZP has been used for framework and different kinds of porcelain for veneering. Hence, we cannot directly compare different clinical studies, but we can still obtain useful information.

Survival Rate

The cumulative survival rate observed was reported from 76.5 % up to 100 %. Salido et al. [37] reported the lowest survival rate in their four-year long follow-up prospective clinical study on 4-unit FPDs made from Y-TZP, and they concluded that at least 4 mm of height is needed for connector thickness. Eleven clinical studies on the other hand reported about 100 % survival rate [22, 23, 25, 26, 27, 28, 31, 32, 39, 45, 48]. The shortest clinical study was the study of Vult von Steyern [22], which lasted only two years. The longest clinical studies, where survival rate was 100 %, are of Molin et al. [26], Crisp et al. [27], Sorrentino et al. [39], Pihlaja et al. [48] and their observation period lasted for 5 years. Among clinical studies, also three longer-term follow-up studies with the observation period of ten years and more, are to be found: Sax et al. [35], Haff et al. [43], Ioannidis et al. [47], where the survival rates of the veneered FPDs are 67 %, 94 % and 85 % respectively.

To the best of our knowledge only three clinical studies have been published correlating posterior FPDs made from metal frameworks (PFM) and zirconia FPDs. Sailer et al. [31] concluded in their three-year follow-up clinical trial that zirconia is a valid alternative to metal framework, but higher rates of clinical complications were found for zirconia FPDs compared to PFM FPDs. Pelaez et al. [38] found zirconia frameworks promising, good periodontal response to zirconia ceramic and patient satisfaction with esthetics, nonetheless the primary complication were veneer fractures. Nicolaisen et al. [57] ended a three-year clinical trial with the observation that PFM FPDs and zirconia

FPDs both have a high survival rate and similar overall clinical performance - three PFM FPDs and five zirconia FPDs have shown chipping fractures with no significant difference (P = 0.44).

Complication

Some biological (secondary caries, endodontic, periodontal) and technical (veneering porcelain chipping, loss of retention, framework fractures) complications have been reported in clinical studies [55]. Biological complications are rather rare. Caries lesions were reported in four different clinical studies [34, 35, 46, 47]. Only five studies reported that abutment teeth needed endodontic treatment [32, 33, 46, 47, 48]. Periodontal problem was mentioned in two studies [34, 47]. Technical complications are more frequent; the most commonly reported complication is chipping or cracking limited to the porcelain veneer [55]. The published porcelain veneering fracture rate in clinical studies varies from 0 % to 39 %. [22, 49]. Eleven clinical studies report about framework fracture from 1 % to 17.6 % [24, 29, 33, 34, 35, 36, 37, 40, 42, 44, 49]. Loss of retention was documented in only three clinical studies [26, 33, 46].

Veneering porcelain chipping

Porcelain chipping and delamination are observed in bilayer restorations where framework was made from Y-TZP zirconia ceramic veneered with porcelain for appropriate esthetic appearance and anatomy contour [7]. Sintering of veneering porcelain might affect the mechanical properties of veneered zirconia FPDs, but might also be favorable as it can fill the surface flaws, generating compressive stresses and increasing the fracture resistance of the FPDs [21]. Fractures of the porcelain veneered to ceramics are more frequent than the porcelain fused to metal [9]. Reasons for that are: higher chemical inertness, less favorable wetting ability, considerably lower thermal conductivity of zirconia ceramics, mismatching coefficient of thermal expansion between zirconia ceramic framework and veneering porcelain, lack of framework support, veneer thickness, inadequate experience with ceramics, firing and cooling rate errors, surface damage from production and sliding contact fatigue during masticatory function [9, 57]. Studies using finite-element analysis (FEA) and fractographic analysis have shown that the highest stress within FPDs is concentrated at the gingival side of the connector area [16, 58]. The weakest point of FPDs during simulation of different loading conditions could be detected by FEA [4]. Therefore, FEA should be recommended in future studies.

To overthrow the complication of chipping, Beuer et al. [33] demonstrated the over-pressing technique for veneering layer of glass ceramic and reported no ceramic chipping after three years. Another proposed solution was the anatomic design of the framework that would grant the support for the veneering porcelain [55]. Frequent repairs or

replacements of chipped FPDs have finally induced the development of full-contour monolithic zirconia FPDs without veneering porcelain [9, 58]. Limited data is available about clinical evaluation of monolithic FPDs, only the data that is at the moment available and states that monolithic zirconia material exhibits fairly low fracture rate up to five years [56]. Although monolithic zirconia may become alternative for bi-layered FPDs made from veneered zirconia, there are still some doubts concerning its esthetic appearance, wear performance and long term reliability [59].

Relevance of In vitro Studies and Clinical Trials

Even though we have a lot of clinical trials and several in-vitro studies , the data correlating the in vitro and in vivo experience are limited. A higher failure rate makes the comparison between clinical data and laboratory results easier [50]. If there is no failure, none of the events can be compared – such as chipping, fracture etc. [50]. It is also important to mention that fatigue tests are always conducted on specimens that are specifically produced for the testing and this production routine might differ from what is done in clinical practice [7]. As for the reliability analysis the strength data may be insufficient because failure in service may occur due to another flaw type [7]. The most reliable option

for acquiring credible and comparable data would be testing identical restorations, simultaneously in vitro and clinically, but unfortunately this is hard to achieve.

Conclusion

From this systematic review, the following could be concluded:

(1) Standardization of in vitro studies and clinical trials is needed. Future studies must use a more systematic approach, such as the uniform use of abutment material, material for simulating periodontal support, data about fracture strength before and after fatigue, number of cycles, information about position and size of the indenter.

(2) There is still lack of clinical studies of monolithic FPDs, which are necessary to follow up the few in vitro studies already conducted.

(3) The new digital techniques in clinical practice should be introduced in further clinical studies for observing wear performance and long term form changes.

Disclosure statement

No potential conflict of interest was reported by the authors.

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